Calibration, Characterization and first Results with the Ocean PHILLS Hyperspectral Imager

Curtiss O. Davis[1], Mary Kappus[1], Jeffery Bowles[1], John Fisher[2], John Antoniades[3] and Megan Carney[4]

[1]Naval Research Laboratory, Code 7212, Washington, D.C. 20375
[2]Brandywine Optical Technologies, P.O. Box 459, West Chester, PA 19381
[3]APTI, 1250 24th St. N. W., Washington, D.C. 20037
[4]SAIC, 4501 Daly Dr., Chantilly, VA

ABSTRACT

The Ocean Portable Hyperspectral Imager for Low-Light spectroscopy (Ocean PHILLS), is a new hyperspectral imager specifically designed for imaging the coastal ocean. It uses a thinned, backside illuminated CCD for high sensitivity, and an all-reflective spectrograph with a convex grating in an Offner configuration to produce a distortion free image. Here we describe the instrument design and present the results of laboratory calibration and characterization and example results from a two week field experiment imaging the coastal waters off Lee Stocking, Island, Bahamas.

Keywords: coastal, imaging spectrograph, oceanography, optical remote sensing, hyperspectral imaging.

1. INTRODUCTION

The Navy is in the midst of a fundamental shift away from open ocean warfare on the sea towards joint operations from the sea. To support that effort the Navy and Marine Corps need methods for determining shallow water bathymetry, topography, bottom type composition, detection of underwater hazards, water clarity and visibility[1].   Visible radiation is the only electromagnetic tool that directly probes the water column, and so is key to Naval systems for bathymetry, mine hunting, submarine detection, and submerged hazard detection. Hyperspectral imaging systems show great promise for meeting Naval imaging requirements in the littoral ocean. To support the development of these applications and to test design features for the Coastal Ocean Imaging Spectrometer (COIS) to be flown on the Naval Earth Map Observer (NEMO) spacecraft[2,3] in 2000 we have designed and built the Ocean PHILLS instrument. This paper discusses the genesis of the Ocean PHILLS instrument, results of laboratory calibration and characterization, and results from the first field campaign to Lee Stocking Island in the Bahamas.

2. DEVELOPMENT OF THE OCEAN PHILLS INSTRUMENT

Over the past six years the Naval Research Laboratory has built a series of hyperspectral imagers (Portable Hyperspectral Imager for Low-Light Spectroscopy or PHILLS).   The first PHILLS instruments used

intensified cameras to deal with low-light conditions. These instruments provided great sensitivity, but they could not to be calibrated due to the variable and changing response of the intensified camera. Unintensified cameras proved useful for other applications, but they were not sensitive enough for imaging the ocean, which is an extremely dark target. Additionally, most cameras were limited to the standard video formats, and provided at most 600 pixels across track, too limited for imaging large ocean scenes. Large format cameras were available, but they were either very expensive or had very slow frame rates (<5 Hz). Bowles, et al.[4] describes three of the earlier PHILLS cameras and their calibration and characterization.

Recent improvements in larger format detector arrays have extended the flexibility of designing high resolution, high signal-to-noise imaging spectrographs, allowing for wider swaths and higher spectral resolution, even for low albedo scenes such as the coastal environment. The Ocean PHILLS uses such a detector in a pushbroom scanned instrument whereby the cross-track ground pixels are imaged with a camera lens onto the spectrometer entrance slit, and the aircraft motion is used to sequentially acquire new lines of the along track ground pixels. The light passing through the entrance slit is dispersed by the spectrograph onto a two-dimensional detector array to obtain the spectrum for each spatial point. The ground sample distance (GSD) in the along-track direction is simply the product of the integration time and aircraft ground speed. The cross-track GSD is approximately the product of fore-optics lens focal length and the detector pixel pitch for a 1X magnification spectrograph. Although the spectrograph is telecentric (with the entrance pupil at infinity) we use a standard C-mount 1" format video lens which is not telecentric. However, for lenses greater than 25 mm effective focal length the vignetting is negligible.

A new spectrograph design has resulted in a major improvement in image quality. The key requirements for the spectrograph are high throughput, low distortion, and high image quality. A grating imaging spectrograph was chosen for its advantages over other hyperspectral technologies such as those incorporating prism, wedge filter, and interferometric techniques[5,6,7]. The primary advantage is the simultaneity in acquisition of linearly dispersed spectrum without the need of post-processing, other than non-uniformity correction of the detector. The main limitations that traditional grating based systems have typically encountered are correcting for apertures faster than f/4, multiple diffraction orders, and polarization effects. Other problems associated with imaging spectrographs are the change of dispersion angle with field position (smile), and change of magnification with spectral channel (spectral keystone). These distortions limit the robustness of subpixel demixing and detection algorithms. The HyperSpec[TM] spectrograph was designed by American Holographic, Inc. (Fitchburg, MA), to meet NRL specifications, and it avoids these problems through the use of an Offner Spectrograph with an aberration-corrected diffraction grating. (Figure 1). The Offner spectrograph design has inherently low smile and keystone distortion due to its concentric design symmetric about the aperture stop[6]. The design was optimized with mirror tilts and the gratings holographic construction point positions as variables, to balance third- and fifth-order astigmatism. The spectrograph is designed with a groove density of 55 grooves/mm; this matches with the camera pixel pitch to produce the desired spectral resolution and range.

The primary selection criterion for the camera were a frame rate of > 30 Hz, high quantum efficiency in the blue (400 – 450 nm), large dynamic range, and low noise. The required format was 1024 spatial pixels by at least 120 spectral channels each 5 nm wide covering the 400-1000 nm spectral region. A thinned, backside-illuminated, split frame-transfer, four readout CCD camera from PixelVision Inc.

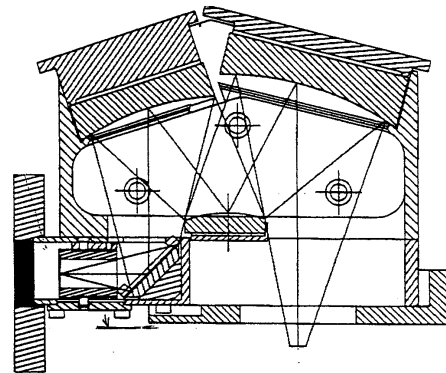| HyperSpec™ VS-15 Specifications	
Size	65 x 80 x 100 mm
Weight	24 oz. (w/o camera or lens)
Field size	12-mm
Dispersion	400–1000 nm over 12-mm
Aperture	f/2
Spot size	< 12-microns rms
Keystone Distortion	< 0.1%
Smile Distortion	< 0.1%
Stray light	< 0.001%
Polarization	< 5 %

Figure 1. Design and specifications for the HyperSpec™ VS-15 Offner Spectrograph.

(Beaverton, OR) was selected. The PixelVision camera had a low noise specification (<30 electrons) and sufficient well depth to meet the SNR and 12-bit dynamic range requirements. The spectrometer dispersion is designed to illuminate only one side of the array (2 of the 4 outputs). The 512 pixels in the spectral direction are normally binned by four on the CCD chip to yield 128 spectral channels. Thinning of the CCD detector allows the photo-generated electrons to be detected closer to the polysilicon gates prior to recombination, thus greatly increasing the quantum efficiency in the blue where silicon strongly absorbs photons. Other attributes of the detector considered in characterization and calibration were the different gains for the two outputs of the array, and frame-transfer smear. Tests showed that these potential artifacts do not adversely impact the overall sensor performance to any measurable degree.

A recent addition to the sensor system was a stabilization mount, which reduces blur introduced by the aircraft vibration during data acquisition. Also, since the 2nd diffraction order of 350-500 nm overlaps the region from 700-1000 nm, a UV/blue absorption filter was placed on the camera window to block that order.

3. CALIBRATION AND CHARACTERIZATION OF OCEAN PHILLS

Characterization.

Understanding sensor performance is critical to extracting the correct information from a data set. Hyperspectral sensor characterization can be divided into the broad areas of spatial image quality, spectral fidelity and radiometric performance. Image quality is similar to that of a typical imager, with metrics of spot size and distortion. Spectral quality can be specified in terms of adjacency artifacts (smile or keystone distortion, blur), and area artifacts (stray light, ghost reflections, multiple orders, and frame transfer smear).

Spectral artifacts can lead to misclassification of spectral signatures. Radiometric performance includes linearity, signal-to-noise (sensitivity), and dynamic range. This ultimately determines the precision and accuracy of the data product. The radiometric performance is a function of wavelength, spatial position, and temporal stability.

The spatial performance was measured with a near-field target with spectral lines, in this case a fluorescent tube masked with a bar pattern (Figure 2a, Table 1). Inherent in the measurement is the inexact nature of the target and the modulation transfer function of the detector itself. The RMS spot size was calculated by fitting a spline curve to the edge response for a range of apertures. Although a range of apertures were tested all of the calibration and field data were collected at f/4. All the measurements were for the 12-micron pixel size of the PixelVision camera. For f/2, the average spot size was 2.5 +/- 1 pixels, For f/4, f/5.6, and f/8 the average spot sizes were approximately 2, 1.5 and 1.5 pixels respectively, with +/- ½ pixel variation across the field. An MTF measurement apparatus would be required to make more accurate measurements.

The spectral attributes for the sensor were measured using a diffuser in front of Helium, Argon, and Mercury, and Oxygen gas discharge lamps. Figure 2b shows the low-pressure Mercury spectrum taken
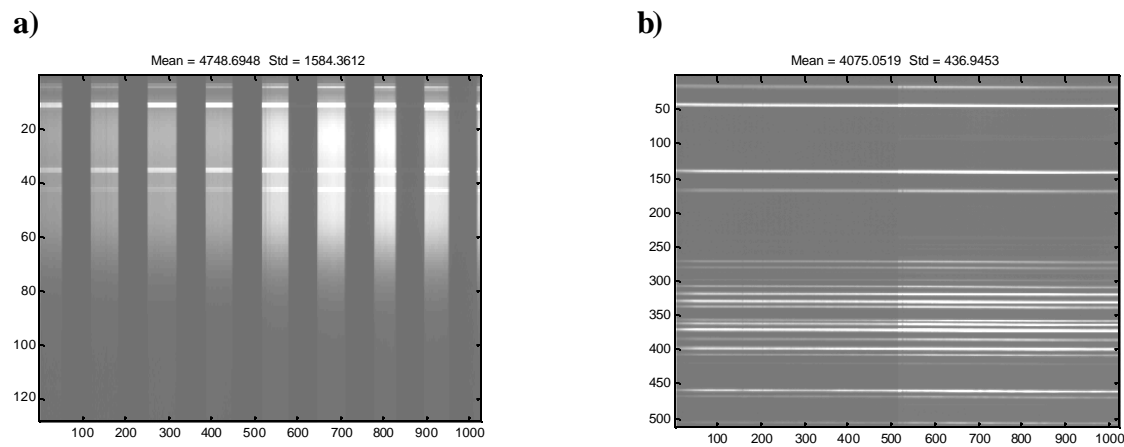
a)

b)

Figure 2. Spatial and spectral images from the laboratory calibration. a) Spatial image of the bar target showing 1024 spatial channels (horizontal) and 128 (512 binned by 4) spectral channels (vertical dimension). b) Image of a low pressure Mercury lamp showing 1024 spatial channels (horizontal) by 512 spectral channels (vertical dimension).

Performance Metric at f/4	Value
RMS Spot size (spatial direction)	2 pixels (24 microns)
RMS Spot size (spectral direction)	2 unbinned pixels (24 microns)
Keystone Distortion	< 1 pixel
Smile Distortion	< 1 pixel
Rotation (center to edge)	1 unbinned pixel

Table 1. Measured performance metrics for the complete system; including lens, spectrograph and camera.

with the Ocean-PHILLS with the 405 nm line at the top of the image. For these measurements the camera is set up so that it does not bin the data in the spectral direction resulting in 512 spectral channels, each 1.13 nm wide. One unbinned pixel of rotation was measured from center to edge, with < 1 pixel of keystone and smile distortions (Table 1). This rotation can be corrected with more accurate alignment techniques.

Spectral Calibration.

Laboratory spectral calibration is performed using the emission lines from Helium, Argon, and Mercury, and Oxygen gas discharge lamps. This is estimated to be accurate to one pixel or 1.13 nm. In the field the spectrum is checked using sharp atmospheric features such as the Oxygen absorption at 762nm and the Fraunhoffer line at 431 nm. These are easily resolved in the unbinned 1.13 nm resolution data. For natural scene data the atmospheric correction is very sensitive to the correct spectral calibration. By adjusting the spectral calibration in 0.1 nm steps to minimize the error spikes around the strong atmospheric absorption features it is possible to adjust the spectral calibration to an accuracy of 0.3 nm.

Radiometric Calibration.

Radiometric calibration is accomplished using a 40" integrating sphere with a blue filter to provide a blue-rich signal more comparable to an ocean scene than the unfiltered sphere output. Data is collected at five settings, 2,4,6,8,and 10 lamps, and for dark current at each setting. A linear least squares fit to the data is used to find the gain and offset. The data is highly linear and using a higher order polynomial does not significantly improve the fit.

4. RESULTS FROM LEE STOCKING ISLAND

The Ocean PHILLS instrument was used in the Office of Naval Research (ONR)-sponsored Coastal Benthic Optical Properties (CoBOP) experiment at Lee Stocking Island, Bahamas in May-June 1999. The focus of CoBOP is the interaction of light with the benthic environment – the seafloor and bottom dwelling organisms – in various environments including sediment, seagrass and coral reefs[8]. In addition to the basic science there is a directed effort in remote sensing for seafloor imaging and classification. The field experiments are designed to coordinate the in situ data collection needed for the basic science initiatives with that needed to provide ground truth for validating the remote sensing images.

A map of Lee Stocking Island and neighboring Norman's Pond Cay is shown in Figure 3. Superimposed are the five flight lines that were flown by the PHILLS aircraft during every flight. The lines run at an angle of 83°, which is aligned with the solar azimuth during the scheduled flight hour of 9:00 - 10:00 am local time. The time of day was selected to achieve a solar zenith angle of about 40° – 55° in order to minimize sun glint, and the direction minimizes differential lighting across the scene. The aircraft used was an Antonov AN-2 Soviet-design biplane, operated by Bosch Aerospace (www.boschaero.com).   The aircraft is capable of sustained

low speeds of 85-90 knots (45 m/s), ideal for maximizing signal level over dark water targets. Lines 1, 2, and 3 are each about 8 km long, and are covered in about 3 minutes. All five lines were generally covered in one hour. Line 4 is 12 km long, extending to the east where the water becomes very deep and suitable for deep water calibration.

The stars on Figure 3 indicate the areas of interest for the basic researchers where extensive "ground-truth" data were collected. The areas include different bottom types – coral, sand, seagrass – sometimes within the same local area, at a variety of depths. Most of the region is quite shallow; the deepest point between the two islands is only 7 m deep. East of Lee Stocking Island the depth increases more rapidly, but the coral reefs at North Perry and Horseshoe are visible through the water. The deep water calibration site, at the end of Line 4 (off the map) is in water hundreds of meters deep where the bottom is not visible. Shipboard measurements of remote sensing reflectance made at the same time as the overflight will be used to validate the aircraft measurements and atmospheric correction.

Figure 3. The five standard flight lines (parallel lines running roughly east to west) flown during the CoBOP experiment at Lee Stocking Island (on right), Bahamas. North is at the top of the map.

Data from all five flight lines were collected successfully on five days. Figure 4 shows part of flight line 2 from June 1, 1999. The characteristics of the different bottom types are visible even in this single-band image from 560 nm. The dark area west of Norman's Pond Cay (inside the box) is the grapestone, which is oolitic sand grains (very fine sands of precipitated calcium carbonate) cemented together. The dark area east of the Cay is relatively deep water, and the bright white areas are shallow shoals, less than 2 m deep, with sandy bottom. There are dark patches of seagrasses near the northwest of Lee Stocking Island. East of Lee Stocking Island are the coral reefs in the area where the image becomes darker. Spectra from the Grapestone area are shown in Figure 4. These have not been atmospherically corrected, and show the radiance at the aircraft. Although they include the path scattered radiance from the atmosphere, there are still very identifiable differences between the bright sandy area, the darker grapestone, and the shallow nearshore region.
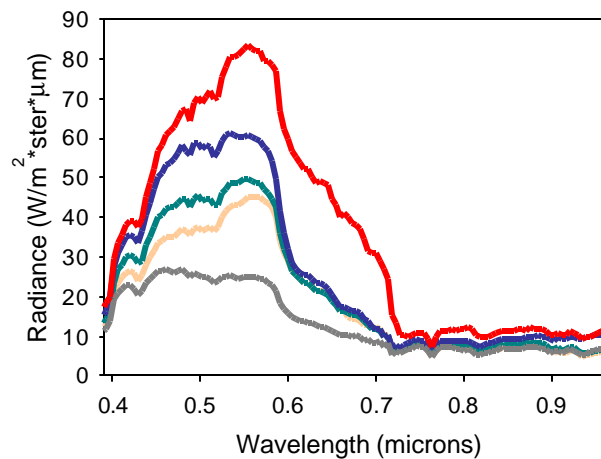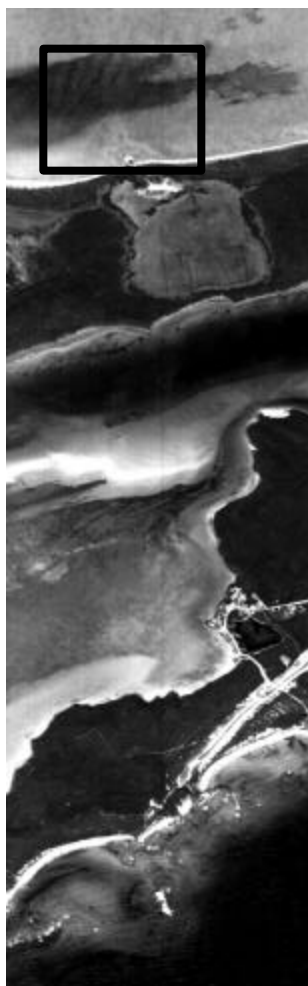

Figure 4. A single band image of flight Line 2 from June 1, 1999. West is at the bottom of the image and East is at the top. Example calibrated spectra taken from the Grapestone area (box) are shown in the graph on the right. The darkest spectra is the grapestone, and the highest signal is from a shallow sandy area.

After calibration, the next step is atmospheric correction. This process is sensitive to atmospheric conditions, some of which – such as aerosol content – are difficult to measure. We are working with a variety of

techniques to make the correction, and we will compare the results to measurements of remote sensing reflectance made from ships. The deep water calibration site will be especially helpful, as it is fairly homogeneous over a large area, and has a known spectral shape due only to water and the phytoplankton (single celled plants) in the water. Since the data must be atmospherically corrected for comparison to ground-truth measurements, the effects of calibration and atmospheric correction are intertwined, and it often requires an iterative process to fine-tune both corrections. Once the data are suitably corrected, they will be analyzed to determine water column properties and bottom type and depth, using the ground-truth data as validation.

5. DISCUSSION AND CONCLUSIONS

The Ocean PHILLS produces high quality spectral imagery. The data has very good sensitivity for ocean scenes. A key element in this success is the VS-15 spectrograph. There is no measurable (< 0.1 pixel over the full field of view) smile or keystone in the imagery. A one pixel rotation over the 1024 pixels of the focal plane is evident in the data. A new more accurate fixture for aligning the camera to the spectrograph is being designed to correct this error. All of the components of the Ocean PHILLS are commercially available. This opens the possibility that a number of people will make similar instruments, making hyperspectral imaging much more widely available for a variety of applications.

ACKNOWLEDGMENTS

REFERENCES

1. Marine Corps Headquarters Letter 3000 of 7 December 1992 validated by CNO (NO96) Letter 3140 Ser 960/3u567444 of 15 January 1993; Special Operations Command letter of 16 April 1991 validated by CNO (NO96) Letter 3140 Ser 960/2U567322 of 22 January 1992.
2. Wilson, T., and C. O. Davis, "Hyperspectral Remote Sensing Technology (HRST) Program and the Naval EarthMap Observer (NEMO) Satellite", *Proceedings of the SPIE*, V. **3437**: 2-10, 1998.
3. Wilson, T., and C. O. Davis, "The Naval EarthMap Observer (NEMO) Satellite", *Proceedings of the SPIE*, V. **3753**, In Press.
4. Bowles, J. M. Kappus, J. Antoniades, M. Baumback, M Czarnaski, C. O. Davis and J. Grossmann, "Calibration of Inexpensive Pushbroom Imaging Spectrometers", *Metrologica*, **35**: 657-661, 1999.
5. Fisher, J., J. Antoniades, C.Rollins, L. Xiang, "A hyperspectral imaging sensor for the coastal environment", *Proceedings of the SPIE*, V. **3482**; 179-186, 1998.
6. Fisher, J., M. Baumback, J. Bowles, J. Grossmann and J. Antoniades, "Comparison of low-cost hyperspectral sensors', *Proceedings of the SPIE*, V. **3438**: 23-30, 1998.

7. Gumbel, H., "System considerations for hyper/ultra spectroradiometric sensors", *Proceedings of the SPIE* V. **2821:** 138, 1996.
8. Mazel, Charles H, "Coastal Benthic Optical Properties (CoBOP) Program Overview, *Proceedings of Ocean Optics XIV*, Kailua-Kona HI, November 10-13, 1998, published on CD by the Office of Naval Research Optics Program.